Improving the longest SI traceable hyperspectral infrared record from space from the AIRS

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1. Contribution of IR sounders to the Global Hyperspectral Infrared Radiance Record

Infrared (IR) sounders measure the upwelling spectrum of the Earth's atmosphere with high spectral resolution as shown in Figure 1. This enables profiling of temperature and water vapor and measurement of concentrations of trace gases from the surface to the stratosphere. The IR sounders, operating today include the Atmospheric Infrared Sounder (AIRS) on the NASA Aqua Satellite, the Cross-track Infrared Sounder (CrIS) on the NASA/NOAA Suomi NPP, and NOAA JPSS Satellites, the Infrared Atmospheric Sounding Interferometer (IASI) on the EUMETSAT MetOp Satellites, and the Hyperspectral Infrared Atmospheric Sounder (HIRAS) on the CMA FY-3 Satellites. All of these instruments are 'hyperspectral', having very high spectral resolution (>1000) to resolve CO_2 and H_2O absorption features used to make temperature and water vapor profiles. The instruments also measure trace gas constituents including O_3, CO, CH_4, SO_2 at various altitudes from the surface to the stratosphere, depending on constituent. The sounders also measure surface temperature and emissivity, cloud top height, cloud liquid water and cloud fraction. The data from these instruments has demonstrated amongst the highest forecast improvement in NWP models of all data types. The data are regularly used in studies of processes affecting weather and climate, validation of weather and climate models, and use in applications including volcano alerts, drought prediction and air quality prediction.

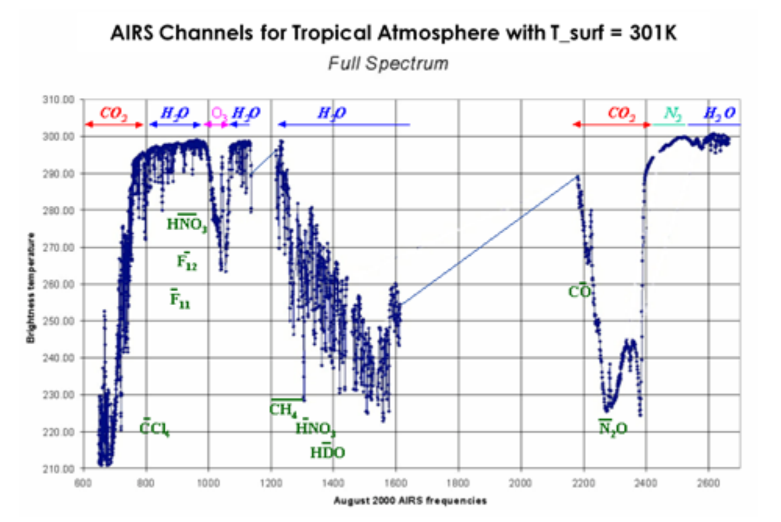
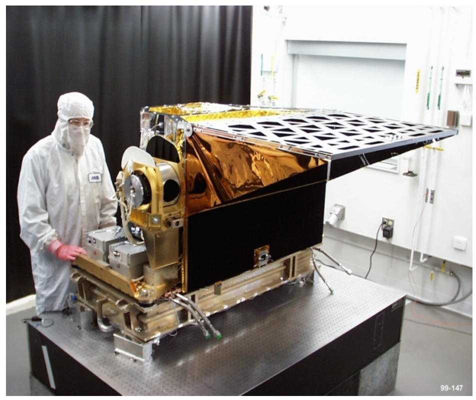


Figure 1. IR Sounders measure the upwelling spectrum with high spectral resolution. Radiances shown are simulated at the AIRS resolution and sampling.

2. The Atmospheric Infrared Sounder (AIRS) on Aqua

The Atmospheric Infrared Sounder (AIRS), shown in Figure 2, is a “facility” instrument developed by NASA as an experimental demonstration of advanced technology for remote sensing and the benefits of high resolution infrared spectra to weather forecasting and science investigations[1]. It was launched into a 1:30 am/pm polar orbit on May 4, 2002 on the EOS Aqua Spacecraft, and is expected to provide highly calibrated data beyond 2024. AIRS has 2378 infrared channels ranging from 3.7 μm to 15.4 μm and a 13.5 km footprint. The AIRS data are used for weather forecasting, climate process studies and validating climate models[2,]. For more information see http://airs.jpl.nasa.gov. AIRS is a vital IR reference sensor for GSICS and is used by JMA for comparison to Himawari 8/9 AHI[3], KMA for comparison to COMS[4], NOAA for comparison to CrIS[5] and GOES[6], and EUMETSAT for comparison to IASI[7].

Figure 2. The Atmospheric infrared Sounder (AIRS) prior to integration with the Aqua Spacecraft.



The AIRS was the first hyperspectral IR sounder designed originally for weather forecasting. The long life of AIRS and the excellent stability of the radiances make them invaluable for climate studies on the seasonal, annual and inter-annual timescales. Use of AIRS in multi-decadal timescales relies on the SI-traceability of the AIRS since a continuous overlap of follow-on sounders cannot be guaranteed indefinitely, and operational sounders may not have the necessary stability and accuracy to propagate the record. The radiances from AIRS are traceable to SI-standards through temperature sensors in the pre-flight calibration Large Area Blackbody (LABB) and Space View Source (SVS) viewed by AIRS during pre-flight testing. During the stepped linearity test, the LABB and SVS are viewed along with the AIRS On-Board Calibrator (OBC) blackbody enabling the AIRS to transfer the calibration of the LABB and SVS to the OBC blackbody.

The AIRS instrument, developed by BAE SYSTEMS, includes a temperature-controlled grating spectrometer and long-wavelength cutoff HgCdTe infrared detectors. AIRS scans the Earth scene up to ±49.5° relative to nadir with a spatial resolution of 13.5 km. The key to the high accuracy and SI traceability of AIRS is the full aperture OBC blackbody and 4 full aperture space views, both viewed every scan. The OBC is a specular coated wedge design with an internal angle of 27.25°. The care taken in the design and development of the AIRS instrument has led to its long life and excellent radiometric stability. Testing performed at BAE system characterized the spatial, spectral, radiometric and polarimetric response of the instrument. The accuracy of the radiometric characterization and the accuracy of the LABB and SVS contribute to the overall accuracy of the system relative to SI-traceable standards.

3. AIRS Radiometric Calibration Approach

The AIRS radiometric calibration approach is straightforward using a nonlinear polynomial fit to observed radiances from the LABB, and a correction for the polarization coupling between the scan mirror and spectrometer that is scan angle dependent. The AIRS Level 1B algorithm converts digital counts to calibrated radiances as follows:[8]

$$L_{ev} = L_{o}(\theta) + \frac{c_0 + c_1'(dn_{ev} - dn_{sv}) + c_2(dn_{ev} - dn_{sv})^2}{[1 + p_r p_t cos2(\theta - \delta)]}$$

Where the radiance offset term depends on the polarization product and phase difference of the scan mirror and spectrometer:

$$L_{o}(\theta) = \frac{L_{sm} p_r p_t [cos2(\theta - \delta) - cos2(\theta_{sv,i} - \delta)]}{[1 + p_r p_t cos2(\theta - \delta)]}$$

In-flight, the gain is then recalculated on-orbit for every scan using the OBC blackbody as follows:

$$c_1{}' = \frac{[\varepsilon_{obc}P_{obc}(T_{obc})-L_o(\theta_{obc})][1+p_r p_t cos2\delta]-c_2(dn_{obc}-dn_{sv})^2-c_0}{(dn_{obc}-dn_{sv})}$$

Where

L_{ev} = Spectral Radiance in the Earth Viewport (W/m2-sr-μm)
c_0 = Instrument offset (W/m^2-sr- μm)
c_1' = Instrument gain (W/m^2-sr- μm-counts)
c_2 = Instrument nonlinearity (W/m^2-sr- μm-counts^2)
dn_{ev} = Digital counts while viewing Earth for each footprint and scan (counts)
dn_{sv} = Digital counts while viewing Space for each scan (counts)
$L_o(\theta)$ = Polarized Mirror Emission Offset. (W/m^2-sr-μm)
L_{sm} = Spectral Radiance of the Scan Mirror for Unity Emissivity at T_{sm} (W/m^2-sr-μm)
$p_r p_t$ =Product of scan mirror and spectrometer polarization diattenuation (unitless)
θ = Scan Angle measured from nadir (radians)
δ = Phase of spectrometer polarization (radians)
ε_{obc} = Effective Emissivity of the blackbody
P_{obc} = Plank Blackbody function of the OBC blackbody at temperature T_{obc} (W/m^2-sr-μm)
T_{obc} = Telemetered temperature of the OBC blackbody (K) with correction of +0.3K.
dn_{obc} = Digital number signal from the AIRS while viewing the OBC Blackbody

The radiometric calibration pre-flight involves measuring the instrument response while viewing the LABB stepped from 205K to 310K. The calibration enables computation of the coefficients and from these and the instrument telemetry we can drive the effective emissivity of the OBC blackbody, OBC temperature correction, and contribution to the radiance from the coupling of the polarization of the scan mirror and the spectrometer, L_o. The calibration is applied independently for all channels and a 5 point running smooth is then applied for each of the 17 independent detector modules of the AIRS instrument. Updates to the calibration have been made recently using pre-flight and in-orbit data to improve the accuracy of the product. These include smoothing of the blackbody emissivity, updates to the polarization parameters, and separate nonlinearity coefficients for the A side and B side detectors. The calibration coefficients computed pre-flight are still used today in the Version 5 Level 1B radiance product delivered at the GES/DISC.

4. AIRS Radiometric Uncertainty

The radiometric uncertainty of the AIRS is calculated by varying each term in the calibration equation in a numerical model and computing the resulting uncertainty due to that term. The uncertainties are then RSS'd to provide a total uncertainty for the radiances. Figure 3 compares the predicted absolute radiometric uncertainty for a scene temperature of 250K of AIRS for radiances from the version 5 L1B, and a future improved version under development (Version 7k). The uncertainty shown is 1-sigma and includes the SI-traceability of the pre-flight calibration target, and the transfer of that to the OBC blackbody of the AIRS instrument. Version 7k has improved the accuracy up to 200 mK in some channels and will be available to the public in late 2020. Results shown here are preliminary, since the uncertainty in the individual terms is still being assessed. They do, however highlight the high accuracy in the current product, and the potential improvement that can be expected in a future version.

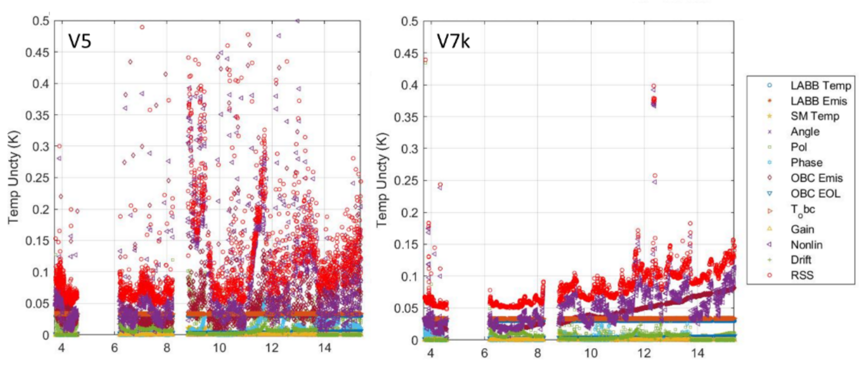


Figure 3. Estimate of the absolute radiometric uncertainty for a scene temperature of 250K for the AIRS L1B radiance product Version 5 (current operational version) (left), and a future Version 7k (right).

Table 1 lists the radiometric uncertainty for the AIRS module centered at 9.14 µm for a scene temperature of 260K. This is one of the worst case modules in V5 due to the uncertainty in the nonlinearity. The high uncertainty arrives from the recent realization that separate A side and B side detector nonlinearity are required for those channels with A-only or B only detectors operating (the average of A side and B side values were used for all channels in Version 5).

Table 1. AIRS radiometric uncertainty (1-sigma) for the worst case module centered at 9.14 µm.

Parameter	Parameter Uncty	Radiometric Uncty (K)
Uncertainty in LABB Temperature	0.03K	0.03K
Uncertainty in LABB Emissivity	0.00005	0.002K
Uncertainty in Scan Mirror Temperature	1.25K	0.006K
Uncertainty in Polarization Amplitude	.0009	0.04K
Uncertainty in Polarization Phase	.08	0.005K
Uncertainty in OBC Blackbody Emissivity	.002	0.07K
Uncertainty in OBC Blackbody Emissivity (EOL)	0.0001	0.004K
Uncertainty in OBC Blackbody Temperature	0.05K	.04K
Uncertainty in Nonlinearity	2.7%*	0.21K
Uncertainty in drift in space view	0.04dn	0.001K
Total Uncertainty at 260K		0.24K

The radiometric uncertainty expressed in terms of temperature depends on the temperature of the scene. Figure 4 shows the dependence of the AIRS radiometric accuracy on scene temperature for the Version 5 product averaged over each module in the AIRS. The center wavelength of the module is shown in the legend. At cold scene temperatures, the uncertainty of the polarization terms begin to dominate. A minimum occurs around 308K for most modules since that is the temperature of the OBC blackbody and the nonlinearity uncertainty vanishes at this temperature.

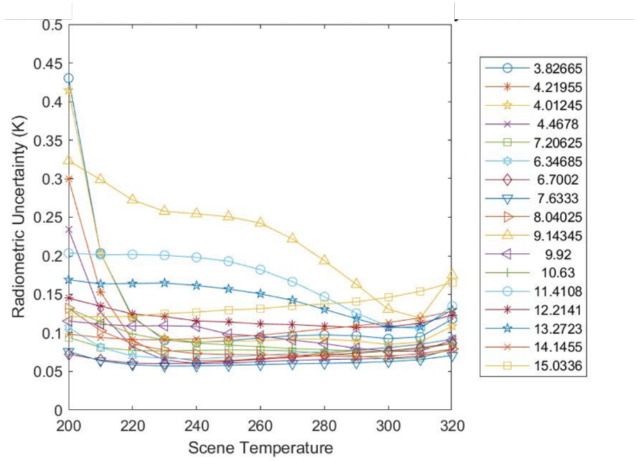


Figure 4. Temperature dependence of the AIRS radiometric uncertainty for each of the AIRS 17 modules.

5. Radiometric Stability and Spectral Calibration

The excellent radiometric stability of the AIRS is discussed in several prior publications[9]. Comparison of AIRS brightness temperatures with sea surface temperatures from the NOAA floating buoy network measured under clear non-frozen ocean conditions shows less than 10 mK/year drift. The AIRS spectrum is calibrated using spectral absorption features in the upwelling spectrum. At present, we have shown the ability to both calibrate to better than 1 ppm and correct the spectra for time varying spectral calibration including Doppler corrections[10]. These corrections along with cleaned and gap filled radiances (using PC reconstruction) will be available in a new Level 1C product expected to be public later this year. For the Level 1B, spectral calibration data are provided separately in calibration properties files by epoch. More information is found in the AIRS Level 1B user guide[11].

6. Conclusions

The AIRS instrument on the EOS Aqua spacecraft provides over 17 years of hyperspectral infrared radiances traceable to SI-standards. The accuracy of the Version 5 product available operationally is 100-400 mK depending on channel, while we expect that a 2x improvement or more is possible in the next version (V7). AIRS V7 L1B is expected to be available in the late 2020 or early 2021 timeframe. While AIRS provides SI-Traceable radiances, the SI-traceability is transferred from the external LABB pre-flight to the OBC blackbody. The transfer adds 50-100 mK of uncertainty to the calibration. This uncertainty can be recovered if the instrument was cross-calibrated in-orbit with an On-orbit SI-Traceable IR Sounder reference sensor. Radiance differences seen between AIRS, CrIS and IASI, that are on the order of 100mK -200 mK, could be reconciled with such a system, facilitating use of multiple instruments in a single application. Improving the accuracy of AIRS radiances reduces errors in science investigations and when compared to model radiances. Reducing errors and biases in the calibration enables reanalysis systems to differentiate instrument biases from model biases. With an expected 20+ year record of SI-traceable, highly accurate, hyperspectral infrared radiances, with global daily coverage, the AIRS radiance record is expected to be extremely valuable to the climate science community. All efforts to improve the accuracy of AIRS and the other hyperspectral IR sounders should be continued and is supported by the IR sounding community.

7. Acknowledgements

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8. References

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